Educational Potential of Experiments on Life Support Systems with Ground-Based Aquatic Habitats

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Abstract

On April 10th 2010, at the Kennedy Space Center, President Barack Obama pronounced his “Remarks on Space Exploration in the 21st Century.” In his speech, the President included life support systems as a technology that “can help improve daily lives of people here on Earth, as well as testing and improving upon capabilities in space.” One of challenges to enable students to conduct research on life support systems is the need for educational capabilities that open up opportunities to learn and experiment with small-scale versions of these systems. Such is the case in higher-education institutions with programs that include courses chemistry, biology, electronics and computer science. These institutions may have educational platforms in their labs to study attributes of robustness or optimality of controllers driving servomechanisms and electric motors, but there is not one that may allow the study of ecophysiological performance of higher plants in closed-loop life support systems, for example. This paper presents aquatic habitats as educational platforms for experiments in life support systems, and the lessons learned while working with undergraduate students at the Human-Automation Systems Lab of the Georgia Institute of Technology. It presents the challenges that these systems pose to students in engineering and sciences, and highlights the opportunities to support higher-education-level teaching and learning of concepts in mathematics, physics, chemistry, and biology.

Keywords:
Science, technology, engineering, and mathematics (STEM) education, small-scale research platform, regenerative life support systems.

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1. Introduction

Our ability to impel long-duration human spaceflight is tied to the capability of habitation systems to process metabolic wastes and regenerate life support compounds, such as oxygen and water[1]. *Regenerative* life support systems (RLSS) include a suite of technologies especially developed to achieve an incremental closure of gaseous and liquid material cycles in space habitats. Such *material closure* increases the autonomy of manned-spacecrafts by reducing the need and frequency of resupply operations. One example of RLSS currently deployed is the Water Recovery System (WRS) in the U.S. segment of the International Space Station (ISS), which recycles liquid wastes (including urine) back into potable (drinking) water. In fact, on April 10th 2010, in a speech titled “Remarks on Space Exploration in the 21st Century,” President Barack Obama challenged:

> “*And we will extend the life of the International Space Station likely by more than five years, while actually using it for its intended purpose: conducting advanced research that can help improve the daily lives of people here on Earth, as well as testing and improving upon our capabilities in space. This includes technologies like more efficient life support systems that will help reduce the cost of future missions.*”

But there is an educational dimension to this challenge that consists in the ability to conduct research on RLSS with small-scale version of these systems to allow students, teachers, and researchers to explore and further define their current problems and long-term issues. Such is the case in higher-education institutions

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with programs in life sciences and engineering, which may own educational platforms to study attributes of robustness or optimality of controllers in robotic systems, but without a small-scale platform to study the ecophysiological performance of higher plants in isolated artificial ecosystems.

1.1. Background

In the past, both public and private organizations have invested in the study of the problems and issues posed by habitats operating in isolation from external sources of air, water, and food. Projects like *Biosphere 2* built by Space Biosphere Ventures and the *Life Support Systems Integration Facility* (LSSIF) of the National Aeronautics and Space Administration (NASA) have combined various life support subsystems with human participants to understand the challenges at a human crew scale. Their purpose has been the been to build artificial ecosystems that may operate during a periods of time comparable to long-duration missions. From single life support technologies to entire biomes, these projects have attempted to integrate various technologies to recycle metabolic byproducts and regenerate consumables. For example, during 1991-1994 *Biosphere 2* integrated six biomes and a human habitat in a volume of 204,000 [m^3]. Figure 1 shows *Biosphere 2* and two other facilities that have aimed to perform experiments relevant to RLSS.

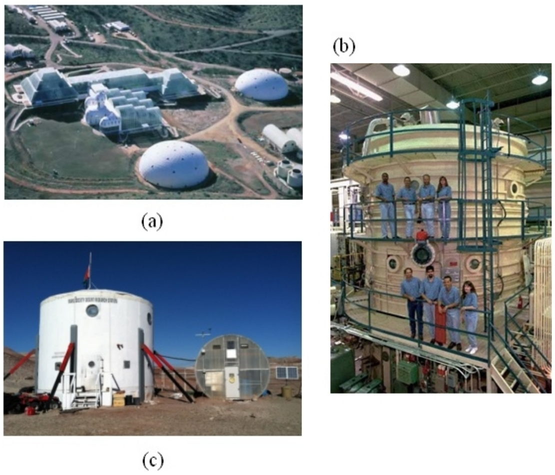

Figure 1: (a) Biosphere 2, (b) Life Support Systems Integration Facility, and (c) Mars Desert Research Station.

During 1995-1997, the LSSIF (displayed in Figure 1(b)) supported crews of four participants in its volume of 226.5 [m^3][2]. In time, the LSSIF initiative transferred its lessons learned to what today is known as the *BIO-Plex* at Johnson Space Center in Houston, Texas. This paper presents small-scale aquatic habitats as research platforms suited for experiments relevant to the operation of RLSS.

Past experiments with the *Closed Equilibrated Biological Aquatic System* (CEBAS) minimodule conducted by the German Aerospace Center (DLR) have made use of aquatic habitats for experiments in zoology and physiology in low Earth orbit (LEO)[3–7], and for ecotoxicological studies in ground-based hardware[8,9]. Results obtained with CEBAS in Space Shuttle missions STS-89 and STS-90 show that microgravity does not affect aquatic organisms considerably for exposure periods of up to 16 days[4]. This module also flew in STS-107[6], but the accident of the Space Shuttle Columbia prevented researchers to obtain data and report additional findings. Yet more recently, scholars from the Chinese Academy of Sciences have employed a *Closed Aquatic Ecosystem*[10,11] (CAES) as well for experiments relevant to ecophysiology, a discipline that “seeks to clarify the role and importance of physiological processes in ecological relations of species[12].” A recent initiative by the Japanese Aerospace Exploration Agency (JAXA) plans to include an aquatic habitat in their International Space Station module, Kibō[13].

2. Description of the HumAnS Lab Habitat

At the Georgia Institute of Technology (Georgia Tech), researchers working at the Human-Automation Systems Laboratory (HumAnS Lab) of the School of Electrical and Computer Engineering (ECE) designed and built the aquatic habitat shown in Figure 2 to perform experiments to RLSS. Its initial purpose has been to better understand the challenges that these systems pose for their manual operation and subsequent automation.

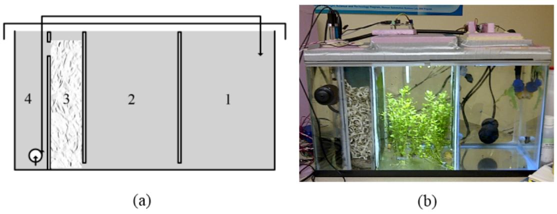

Figure 2: (a) Recirculation diagram of the habitat; (b) Physical realization of the habitat.

Experiments performed at the HumAnS Lab focus on the process of respiration, by which 15 snails of the genus *Pomacea* consume O_2 while exhaling CO_2 as a byproduct. Complementary, plants of the species *Bacopa Monnieri* make use of the CO_2 to produce O_2

through photosynthesis, which is promoted by a 6-LED lamp of 300 [lm] and 90° view angle. The plants supply the O_2 needed by snails and bacteria while aiming to maintain an acceptable concentration measured in [mg/L] in the habitat. Water serves as the medium in which these quantities are stored (dissolved), and through which they are exchanged between the organisms.

The habitat consists of a 10-gallon tank divided in four compartments by three separators (see Figure 2a); the first two with an opening area of 12.60 [cm^2] at the bottom and the third with a 48.00 [cm^2] on the top side. Further details about the design of the habitat have been discussed in previous work[14]. The first and second compartments contain animals (consumers) and plants (producers), respectively. Snails are fed regularly with sinking algae tablets. The third compartment contains Bio-Fill™, active carbon, and water filtration foam serving as the media for biological, chemical, and mechanical filtration, respectively. The fourth compartment allows access for sensors and the water pump. The environmental sensors installed include dissolved oxygen (DO), pH, and ORP. The water circulates through the four compartments. The first compartment has a motorized hatch of 10cm×10cm and an aerator that allow for reconfigurability, making the system open (volatile) or closed (non-volatile) if necessary; this mechanism is triggered as a fail-safe mechanism when the DO levels reach a minimum of 2.0 [mg/L]. The second compartment holds the LED-lamp and gives access to a dosifier pump that provides a sodium bicarbonate solution to increase the carbonate hardness (kH) of the water; the changes in kH are monitored through variations of the pH readings. Measurements from the sensors are processed by a computer/controller operating under LabVIEW®. The controller delivers the control signals that regulate the LED-lamp power via a pulse-width modulation (PWM) board, and also controls the hatch, and the air and dosifier pumps. The control signals can be generated by control laws or driven manually through a graphical user interface (GUI).

3. Educational Challenges and Opportunities

During two years, six undergraduate students worked at the HumAnS Lab (three each year) through the Opportunity Research Scholars (ORS) Program of the School of ECE at Georgia Tech. During this time, the students gained hands-on experience in the construction and simulation of the HumAnS Lab Habitat. This Section describes some of the educational challenges and opportunities observed from this experience. The most important challenges to report so far are presented in Table 1, together with the opportunities to enhance the educational potential aquatic habitats for education and research initiatives in support of RLSS. The following Subsections elaborate in each one of these before summarizing the lessons learned in Section 4.

	Challenges	Opportunities
1:	Ethics in life science research	Use of invertebrate models (snails) and simulations.
2:	Ecophysiology	Learning about stress, adaptation, homeostasis, and sustainability.
3:	Closed-loop systems	Mathematical modeling, physics, chemistry, biology, and control.
4:	Slow-time response	Simulation tools and approaches.
5:	Human-system interaction	Psychology, cognitive engineering, and user-centered design.
6:	Science communication	Work in multidisciplinary teams.

Table 1: Challenges and opportunities for education and research with aquatic habitats

3.1. Challenges

This Subsection briefly describes the challenges presented in the left-side column of Table 1.

3.1.1. Ethics in RLSS research

Working with aquatic habitats, one would assume the possibility to work with fish and other vertebrate models of *consumers*. However, the Georgia Tech *Institutional Animal Care and Use Committee* (IACUC) encourages the replacement of these animal models with invertebrate species or other means of experimentation, such as computer simulations, due to the risk of stress that vertebrates may unnecessary develop during tests, or the possibility of fatalities. This is one of the three-R's policy in support of the *replacement*, *reduction*, and *refinement* in experimental design to address ethical issues in life science research. Therefore, experiments performed with the HumAnS Lab Habitat make use of snails instead of fish as the consumer model. Furthermore, the physical platform is only used to develop mathematical models for simulation in MATLAB Simulink® and for validation of parameters.

3.1.2. *Ecophysiology*

Ecophysiology is the field of knowledge that “seeks to clarify the role and importance of physiological processes in ecological relations of species.”[12] In this direction, the challenge consists of deciding which species should be included in the aquatic habitat, and which should not. For example, one may choose to work with a certain species of higher plant to generate oxygen that exhibits a faster growth rate than others. Depending on the experiment to be performed, this may be an advantage or a disadvantage. Such plants may need to be trimmed too often, requiring human intervention and interruption of system closure. Another example can be offered about consumers: a certain kind of shrimp species may not produce enough CO_2 for the plants, hindering the success of experiments that focus on the process of respiration. Therefore, from the ecophysiological perspective, the selection of species is a challenge for experiments with aquatic habitats.

3.1.3. *Closed-loop Systems*

A goal of RLSS is to achieve a high degree of material closure by recycling metabolic byproducts and regenerating life support consumables. For ground-based experiments, aquatic habitats offer the advantage of enclosing a volume of water that serves as a medium in which aquatic regenerative processes take place. Another advantage is the availability of mature technology and commercial products to support such research platforms. However, a challenge of system closure goes beyond the possibility of building a habitat that operates in isolation. The experience of Biosphere 2[1], and the recent anomaly on the Water Recovery System on ISS[15], have shed light on an additional challenge for future space habitats: system closure promotes unintended chemical interactions that may result in the depletion of life support consumables, deterioration of regenerative processes, or the accumulation of unknown or unidentified chemical compounds. This challenge alone poses questions that will require multidisciplinary efforts to find answers, and thus enable the safe and autonomous operation of future space habitats.

3.1.4. *Slow-time Response*

Life support processes generally take considerable time, i.e. they have relatively large time constants and slow responses. An example is shown in Figure 3 in which a simulation similar to experiments performed with the CEBAS minimodule are validated in the research platform during a period of time of seven days. The Figure shows the evolution of the dissolved oxygen and the pH in the aquatic habitat (in colors) compared to the computer simulation (in black).

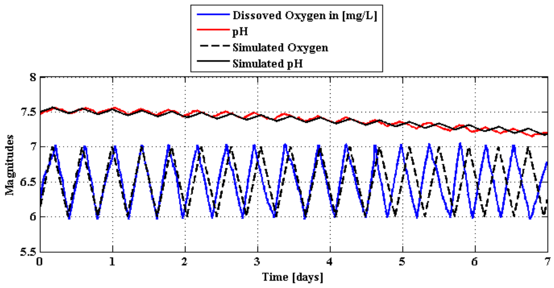

Figure 3: Validation of a Blüm-type experiment.

The slow-time response of the aquatic habitat, as well as other regenerative systems, sets limitations to the amount of time and attention that investigators may dedicate to real-time experiments in an educational setting. Although one of the goals is to understand how RLSS will work in conjunction with human operators, educational activities need to take place in shorter and controlled period of time. Therefore, there is the need to accelerate experiences through other means, which still may make use of the real-time platform to validate approaches and results.

3.1.5. *Human-System Interaction*

In the same direction as in the previous challenge, experiments relevant to the performance of humans interacting with the system may be considerably expensive in terms of time, attention, and cost. Although such interaction may raise questions about how attention may affect the performance of RLSS, other human performance indicators may be tested without such expense, such as perception, situation awareness, decision making, and action selection.

3.1.6. *Science Communication*

As noted in Subsection 3.1.3, issues such as material closure in future space habitats requires the attention of specialists in various fields of knowledge to address problems in a multidisciplinary fashion. One challenge for team building is good communication. This is especially the case in teams with members of various disciplines, who may use jargon from their own field. Because such endeavors may involve a variety of fields of knowledge, communication may also require additional efforts in order to enable a successful exchange of ideas. Such challenge is evident in discussions that make use of different terminology to express similar concepts. Such exchanges result in additional resources invested to ensure clarity and consistency in communication. In an educational setting, where students may not have experience addressing this problem, communication may become a challenge as well and the source of frustration.

3.2. *Opportunities*

This Subsection briefly describes the opportunities presented in the right-side column of Table 1.

3.2.1. *Use of Invertebrate Models and Simulations*

In response to the ethical challenge of using non-invertebrate models in research with the aquatic habitat, snails have become the primary animal model for experiments on respiration. They were able to replace vertebrates and exhibited attributes useful for experiments in RLSS automation and control. Snails are relatively inexpensive and may feed from growing algae. Algae tablets are commercially available as well.

3.2.2. *Learning about Stress, Adaptation, Homeostasis, and Sustainability*

When faced with the need to make use of snails as the animal model, it was apparent that snails did more than eating and breathing. They undergo periods of aestivation, i.e. periods of metabolic depression in which they reduce their rate of oxygen consumption. This phenomena introduced disturbances in the accumulation and depletion of dissolved oxygen in the water, and provided the opportunity to approximate the animal model as a stochastic system. As an example temporal response showing the varying characteristic of the rate of oxygen accumulation and depletion caused by the respiration of snails is shown in Figure 4, which corresponds to the derivative of the dissolved oxygen signal shown in Figure 3. The simulation assumes constant rates of consumption and production.

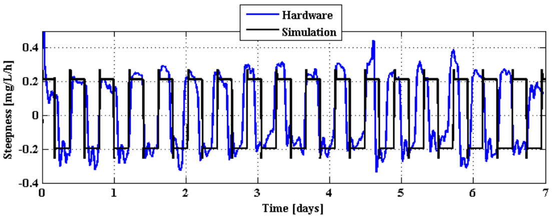

Figure 4: Rate of accumulation/depletion of dissolved oxygen in the aquatic habitat.

3.2.3. *Mathematical Modeling, Physics, Chemistry, Biology, and Control*

Given the slow time response of aquatic habitats and RLSS in general, one of the educational opportunities is to develop the skills to mathematically describe these systems. Such models make use of differential equations taught in all engineering programs and enable their simulation and numerical analysis. For example, the physico-chemical description of the aquatic habitat[14] should include concepts and equations describing phenomena such as mass transfer, balance, and diffusion. As an illustration, the concept of mass balance can be studied as described by Figure 5 and Equations 1 for an open and Equation 2 for a closed system.

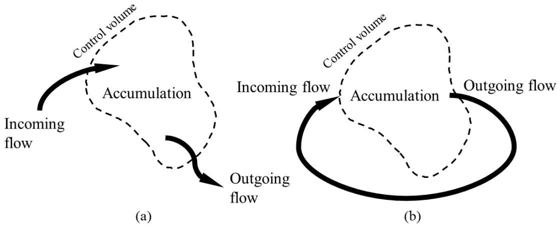

Figure 5: Mass balance in open (a) vs. closed (b) systems.

$$V\dot{[x]} = F_{in}[x]_{in} - F_{out}[x]_{out} \tag{1}$$

$$V\dot{[x]} = F_{rec}\left([x]_{in} - [x]_{out}\right) \tag{2}$$

Beyond physico-chemical phenomena, plants and snails in a aquatic habitat may differ in their performances depending on environmental factors and availability of food and nutrients. These variations introduce disturbances, non-linearities and time-varying characteristics into the system that, if modeled, open up opportunities for experiments relevant to control and automation of dynamic systems. An example of a non-linear phenomena from biology is the light-response curve of higher plants illustrated in Figure 6 and described by Equation 3.

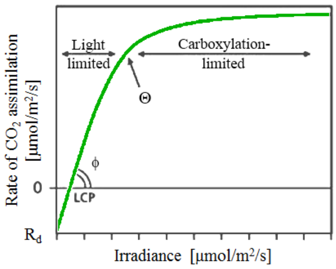

Figure 6: Light-response curve of photosynthesis to irradiance[16].

$$\begin{aligned} A &= -R_d + \frac{\phi \cdot I + A_{max}}{2 \cdot \Theta} - \\ &- \frac{\sqrt{(\phi \cdot I + A_{max})^2 - 4 \cdot \Theta \cdot \phi \cdot I \cdot A_{max}}}{2 \cdot \Theta} \end{aligned} \quad (3)$$

In Equation 3, A represents the assimilation rate in [μmol/m^2/s], I is the irradiance in [μmol/m^2/s], ϕ is the slope or the light-limited region, Θ determines the point of saturation by carboxylation, A_{max} is the upper boundary of assimilation, and R_d is the dark respiration of the plant. The light compensation point (LCP) in Figure 6 represents the irradiance value in which photosynthesis and dark respiration have equal magnitudes and result in a zero net assimilation of CO_2. The ability to model and describe such phenomena allows to study their effect in the design of adaptive and robust controllers. Some illustrative results on the study of non-linearities are shown in Figures 7 and 8.

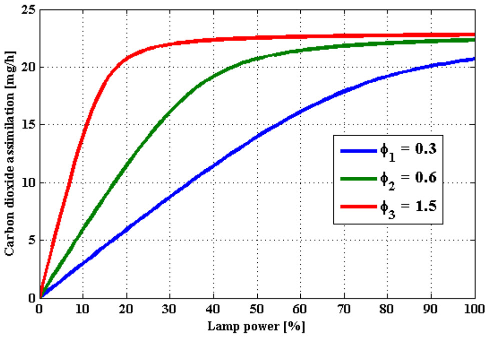

Figure 7: Comparison of light-response curves with various Φ.

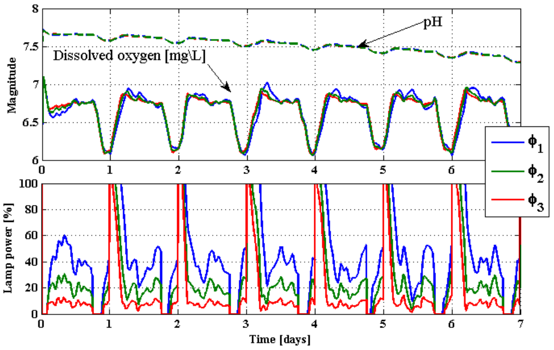

Figure 8: Comparison of temporal responses of controlled closed-systems with non-linearities light-response curves.

Such challenge opens the opportunity to use mathematical tools, such as differential equations and integral transforms, to describe the dynamic behavior of physico-chemical and biological phenomena. The ability to obtain a mathematical model of these systems also allows the design of controllers and fail-safe/fail-operational mechanisms to ensure proper performance and management of anomalies, all of these also critical in larger-scale RLSS. In addition, introducing capabilities for chemical analysis in experiments with ground-based aquatic habitats may provide new insights and enable approaches for the material closure problem described in Section 3.1.3 at a lab-bench scale.

3.2.4. *Simulation Tools and Approaches*

Having mathematical models of physico-chemical and biological elements allows to overcome the slow-time response challenge of the aquatic habitat. Simulations make use of such models to predict the behavior of the system and the performance of controllers and protection systems. Students have the opportunity to implement the model in simulation software and learn how to implement, interpret, and communicate experiments, predictions, and results. Figure 9 shows and example of the simulation of the aquatic habitat in MATLAB Simulink®.

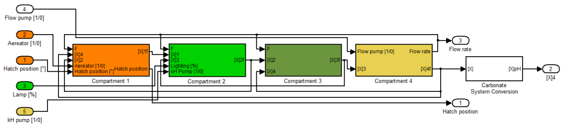

Figure 9: Simplified block diagram of the simulation of the aquatic habitat

3.2.5. *Psychology, Cognitive Engineering, and User-Centered Design*

Simulation software also offers the opportunity to design user interfaces to study and explore the interaction of human operators, either experts or non-experts, with RLSS. Such opportunity, highlights the problems and issues that need to be solved in order to enable human operators to gain awareness about the situation of systems. It also enables students and researchers to evaluate and explore solutions to the anomalies that emerge in the operation of RLSS, such as the WRS anomaly mentioned in Subsection 3.1.3.

3.2.6. *Work in Multidisciplinary Teams*

By working with a system that involves chemistry, biology, electronics, computing, sensing, and automation, students from a variety of fields may contribute to the multidisciplinary understanding, approach, and solution of problems relevant to the operation and challenges of RLSS.

4. Lessons Learned

Making use of an aquatic habitat for education and research on RLSS poses challenges for students, both graduate and undergraduate, who are faced with the need to independently and simultaneously learn and integrate concepts from various fields of knowledge. This may require guidance and mentoring by experts in those fields, together with training in multidisciplinary communication to promote a successful exchange of ideas. If teams of undergraduate students are involved, communication will be especially important in order to define the research problem in such a complex domain. As students and young researchers, their priority should be to understand the research questions first, so that they may brainstorm and propose alternative approaches and solutions to specific problems. Beyond this, good teamwork and team ethics are *essential* as in any other multidisciplinary endeavor in higher-education.

5. Conclusion

Although there is no educational lab-bench platform available to perform undergraduate and graduate level research on the operation of RLSS, aquatic habitats show promise to allow students, teachers, and researchers to explore and further define their current problems and long-term issues. This paper presented the educational challenges and opportunities posed by the use of an aquatic habitat as a research platform, and highlighted some of the concepts, principles, and skills that may be taught.

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